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Abstract

Pedo-transfer functions are largely used in soil hydraulic characterisation of large areas. The use of physico-empirical approaches for the derivation of soil hydraulic parameters from disturbed samples data can be greatly enhanced if a characterisation performed on undisturbed cores of the same type of soil is available. In this study, an experimental procedure for deriving maps of soil hydraulic behaviour is discussed with reference to its application in an irrigation district (30 km^2) in southern Italy. The main steps of the proposed procedure are: i) the precise identification of soil hydraulic functions from undisturbed sampling of main horizons in representative profiles for each soil map unit; ii) the determination of pore-size distribution curves from larger disturbed sampling data sets within the same soil map unit; iii) the calibration of physical-empirical methods for retrieving soil hydraulic parameters from particle-size data and undisturbed soil sample analysis; iv) the definition of functional hydraulic properties from water balance output; and v) the delimitation of soil hydraulic map units based on functional properties.

Introduction

Accurate simulation algorithms for the description of soil water flow processes have been developed for use in many environmental and agricultural studies (Feddes *et al.*, 1988; Beven, 1989; Santini, 1992). If correctly implemented, such models may provide satisfactory predictions of water balance terms and may be used to simulate different water management scenarios.

A major difficulty in the application of hydrological modelling techniques at a regional scale is the lack of reliable information concerning soil hydraulic parameters. Hydraulic characterisation of undisturbed soil samples can be very expensive and time-consuming, especially when the spatial variability of soil properties in large areas has to be investigated (Warrick and Nielsen, 1980). As a consequence, simplified characterisation techniques based on the analysis of more easily measurable parameters, such as textural data, has found renewed interest (van Genuchten *et al.*, 1992). A great advantage of this approach is that soil survey data from pedological studies are widely available and distinguish different soil units with defined boundaries. Indeed, hydrological simulation models at regional scale are generally based on soil maps with limited information about the soil hydraulic behaviour (Bui *et al.*, 1996; Webb and Rosenzweig, 1993; Srinivasan and Arnold, 1994; Barringer *et al.*, 1995; Schultz and Ritchie, 1996). Recently, efforts have been made to build comprehensive archives relating laboratory observations of soil water retention and conductivity to other soil physical data derived from pedological surveys (European Commission, 1994).

The effectiveness of this approach depends on the accuracy in predicting soil hydraulic properties, and the precision of the required output, according to the specific application or model being applied. Any indirect method for predicting soil hydraulic characteristics from basic soil data needs validating for the specific local conditions and soil types; indeed, information on soil texture alone is not sufficient to describe hydraulic behaviour accurately, especially in structured or finely textured soils. Once the soil hydraulic properties of a profile have been defined from other soil physical data, the effects of variability of soil physical properties on the results have to be evaluated. Thus, a suitable criterion for comparing the output of the chosen algorithm for different soil profile parameters is required, for example by defining some *'functional properties'*, which describe the hydrological behaviour of the entire soil profile (Wösten *et al.*, 1986). These functional properties can be derived from the output of hydrological models, assuming specific water management criteria and boundary conditions (Hack-ten Broeke and Hegmans, 1996).

The present study proposes a procedure for mapping the hydrological behaviour of agricultural land based on: i) the prediction of soil hydraulic properties from pedological surveys and easily measurable soil physical properties and ii) evaluation of the output from a one-dimensional water flow model in terms of easily comparable functional properties, such as the number of days required to reach a fixed value of potential at a certain depth under defined upper and lower boundary conditions. The procedure consists of the following steps:

- calibration of a simplified model for deriving soil hydraulic properties from textural data;
- application of the calibrated model for evaluating the soil hydraulic characteristic curves of retention and conductivity in selected locations within each soil map unit;
- derivation of functional properties from soil water balance simulations;
- delimitation of homogeneous soil hydraulic areas from the spatial distribution of functional properties.

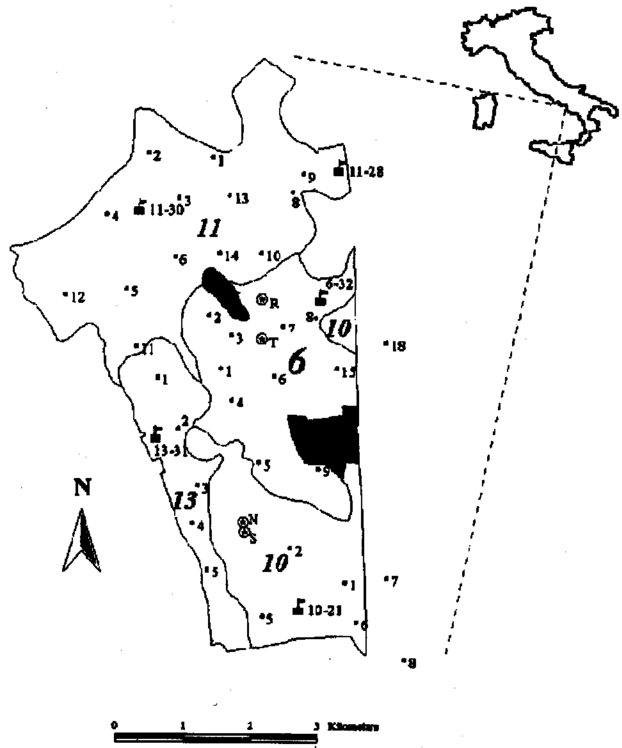

Fig. 1. *Soil map unit boundaries and sampling locations. Shadow zones represent urban area, bold large numbers represent soil pedological units, flags indicate representative soil profile, (●) represents sampling locations and (⊗) represents control sampling locations.*

Procedure Description and Application

DATA ACQUISITION AND LABORATORY INVESTIGATION

The methodology in question was applied to an irrigation district in southern Italy (Fig. 1), where a soil map at a scale of 1:10 000 was already available (Aru and Baldaccini, 1984). The soil map was obtained by applying standard procedures (photo-interpretation, basic geological and geomorphological maps, soil survey and classification). The case-study area of approximately 30 km^2 comprised 4 soil map units, the representative soil profile characteristics of which are shown in Table 1.

A soil survey and sampling campaign was carried out at several locations distributed throughout the study-area. Both undisturbed and disturbed soil samples were collected.

For each profile reported as representative of the corresponding soil map unit, undisturbed soil cones of height 9 cm and diameter of 8.5 cm were extracted from main horizons by a steel cylindrical sampler. The laboratory technique for determining the soil water retention curve is similar to the classical evaporation method of Wind (Boels *et al.*, 1978),

Table 1. Main soil reference profiles characteristics and relative classification. O.M. is the organic matter content and B.D. is the bulk density.

Unit	Profile	Soil Classification USDA	Horizon	Depth cm	Sand %	Silt %	Clay %	$CaCO_3$ %	O.M. %	B.D. g cm^{-3}
6	32	Typic Calcixeroll	Ap1	0–30	47.9	27.0	25.1	32	4.35	0.97
			Ap2	30–60	54.2	25.5	20.3	19		0.96
			Ckm	60–120	23.3	42.5	34.2	88		0.98
10	21	Calcixerollic Xerochrept	Ap	0–40	29.4	35.1	35.5	25	3.00	1.46
			B2	40–70	30.9	27.9	41.2	14		1.10
11	28	Aquic Xerofluvent	Ap	0–70	33.9	27.5	38.6	17	2.95	1.30
			A1	70–90	65.1	6.0	28.9	13		1.50
11	30	Aeric Fluvaquent	Ap	0–45	5.2	35.6	59.2	2	3.30	1.35
			A1	45–85	5.6	30.1	64.3	7		1.41
13	31	Typic Fluvaquent	Ap1	0–30	13.4	31.1	55.5	12	1.95	1.32
			Ap2	30–70	6.2	39.1	54.5	12		1.38

Table 2. Reference soil profile parameters describing $\theta(h)$ and $k(h)$ relationships.

Unit	Profile	Soil Classification USDA	Horizon	Depth cm	θs $cm^3\ cm^{-3}$	θr $cm^3\ cm^{-3}$	n –	α_{VG} cm^{-1}	K_s $cm\ h^{-1}$
6	32	Typic Calcixeroll	Ap1	0–30	0.644	0.000	1.132	0.194	15.00
			Ap2	30–60	0.622	0.000	1.176	0.048	20.00
			Ckm	60–120	0.617	0.000	1.205	0.005	0.42
10	21	Calcixerollic Xerochrept	Ap	0–40	0.463	0.162	1.198	0.147	45.00
			B2	40–70	0.580	0.112	1.272	0.049	8.80
11	28	Aquic Xerofluvent	Ap	0–70	0.472	0.199	1.335	0.106	11.00
			A1	70–90	0.429	0.188	1.328	0.037	1.80
11	30	Aeric Fluvaquent	Ap	0–45	0.507	0.138	1.320	0.035	1.30
			A1	45–85	0.559	0.235	1.300	0.023	0.35
13	31	Typic Fluvaquent	Ap1	0–30	0.496	0.210	1.463	0.037	0.30
			Ap2	30–70	0.484	0.142	1.136	0.188	80.00

as described by Wendroth *et al.* (1993); its application is reported in detail by Basile and D'Urso (1997).

Saturated hydraulic conductivity, k_s, was determined on the same set of samples using the falling-head permeameter method. The parameters of the analytical expression (van Genuchten, 1980) for the soil water retention curve measured in the laboratory and the k_s values are given in Table 2. Subsequently, the samples were dried and destroyed to determine bulk density and the particle-size distribution curve. Texture analyses were performed with the hydrometer method (for the size range between 0.002 and 0.5 mm) and wet sieving (0.5–2 mm).

Disturbed soil samples were collected from the different soil horizons at 40 locations to determine the particle-size distribution curve, by the procedure described above.

The textural data thus collected were used to verify and improve the delimitation of the soil map units. In particular, unit 11 was divided into two sub-units; furthermore, in two sites of unit 13 (namely location 4 and 5) textural data suggested close similarities with the samples collected within unit 10. Part of unit 13 was thus merged with unit 10. The results of textural analysis of disturbed and undisturbed samples for the corresponding reference profile are illustrated in Fig. 2, which describes the textural variability of the Ap horizon of soil unit 10.

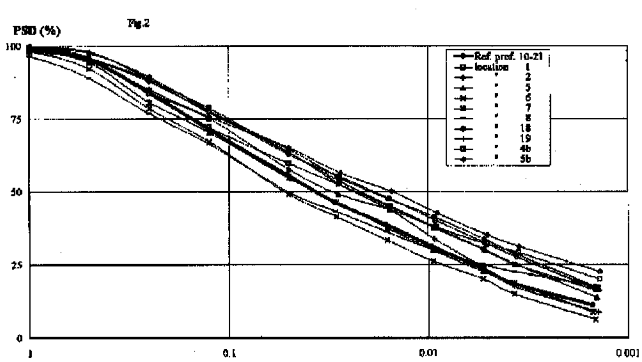

Fig. 2. *Particle-size distribution curves for Ap horizon for mapping unit 10 with reference profile 21.*

CALIBRATION OF A SIMPLIFIED MODEL FOR DERIVING SOIL HYDRAULIC PROPERTIES FROM TEXTURAL DATA

Soil Water Retention

Several methods are available for predicting soil hydraulic properties from other physical characteristics (van Genuchten *et al.*, 1992). Two main categories may be defined: I) purely empirical methods, derived from regression analyses of experimental observations (e.g. Gupta and Larson, 1979; Rawls *et al.*, 1982; Vereecken *et al.*, 1989); and II) physico-empirical models, attempting to give a physical significance to the relationship between the chosen parameters (i.e. particle-size distribution, bulk density, etc.) and the soil hydraulic characteristics (Arya and Paris, 1981; Haverkamp and Parlange, 1986). The latter approach is used in this study.

Models describing the soil water retention are based mainly on the schematisation of pore-size distribution in relation to particle-size distribution; due to the complexity of soil water retention mechanisms, especially in fine-textured and structured soils, empirical adjustments are required. Nevertheless, the physico-empirical models, such as the Arya and Paris method (Arya and Paris, 1981; Arya and Dierolf, 1992), can be generalised more easily than purely empirical techniques.

On the assumption that the soil water retention curve, SWRC, and the particle-size distribution curve, PSD, have a similar shape, Arya and Paris related the pore radius, r_i, to the particle radius, R_i, in a generic i^{th} textural class by means of the following relationship:

$$r_i = R_i\sqrt{4en_i^{(1-\alpha)}/6} \quad (1)$$

where α is an empirical parameter which is given a constant value equal to 1.38, e is the void ratio and n_i is the number of spherical particles in the i^{th} range. This latter quantity can be determined from the solid mass fraction W_i corresponding to the particle radius R_i in the following expression:

$$n_i = \frac{3W_i}{4\pi R_i^3 \rho_p} \quad (2)$$

where ρ_p indicates the particle density.

The α parameter was introduced in Eqn. 1 for considering the geometrical differences between a uniform packing of spherical particles and a natural soil. In fine-textured soils, Basile and D'Urso (1997) found that α cannot be assumed as constant, but is dependent on the water potential h. Furthermore, they found that the $\alpha(h)$ relationship is specific to each type of soil and may be assumed to represent the overall effect of soil internal structure on the hydraulic behaviour of the horizon. The $\alpha(h)$ relationship for a given horizon of a soil map unit can be estimated from retention and particle-size data of reference undisturbed samples (Basile and D'Urso, 1997). By combining Eqn. 1 and the capillary function, relating the pore diameter r_i to the potential h, it is possible to determine, for each particle-size diameter R_i, the value of α which satisfies simultaneously the observed retention function and Eqn. 1. Thus, a bi-univocal correspondence between α and h is established.

This procedure was applied to the soil horizons of each profile associated with a sub-unit; different analytical expressions were used to fit the $\alpha(h)$ data. The resulting relationship is illustrated in Fig. 3a and 3b for the top layer respectively of units 10 (reference profile 21) and 11 (reference profile 28). It was confirmed that parameter α could not be assumed constant, and different analytical expressions were used to best fit the $\alpha(h)$ function. In some cases not shown, such as the sub-surface horizon of units 10 with a 64% sand fraction, it was possible to consider α = 1.38 in agreement with the original Arya and Paris assumptions.

Unsaturated Hydraulic Conductivity

The indirect estimation of hydraulic conductivity is more difficult than the SWRC and greater inaccuracy should be expected, as reported by different authors (van Genuchten and Leij, 1992; Mualem, 1992). Restrictions to the application of indirect methods arise from the fact that the capillary equation is not able to explain entirely the complex mechanism of water conduction through soils (Kutilek and Nielsen, 1994).

If water retention data are available, the soil hydraulic conductivity may be derived according to the theoretical approach of Mualem (1976). This model combines an empirical S-shaped curve for the SWR function with the

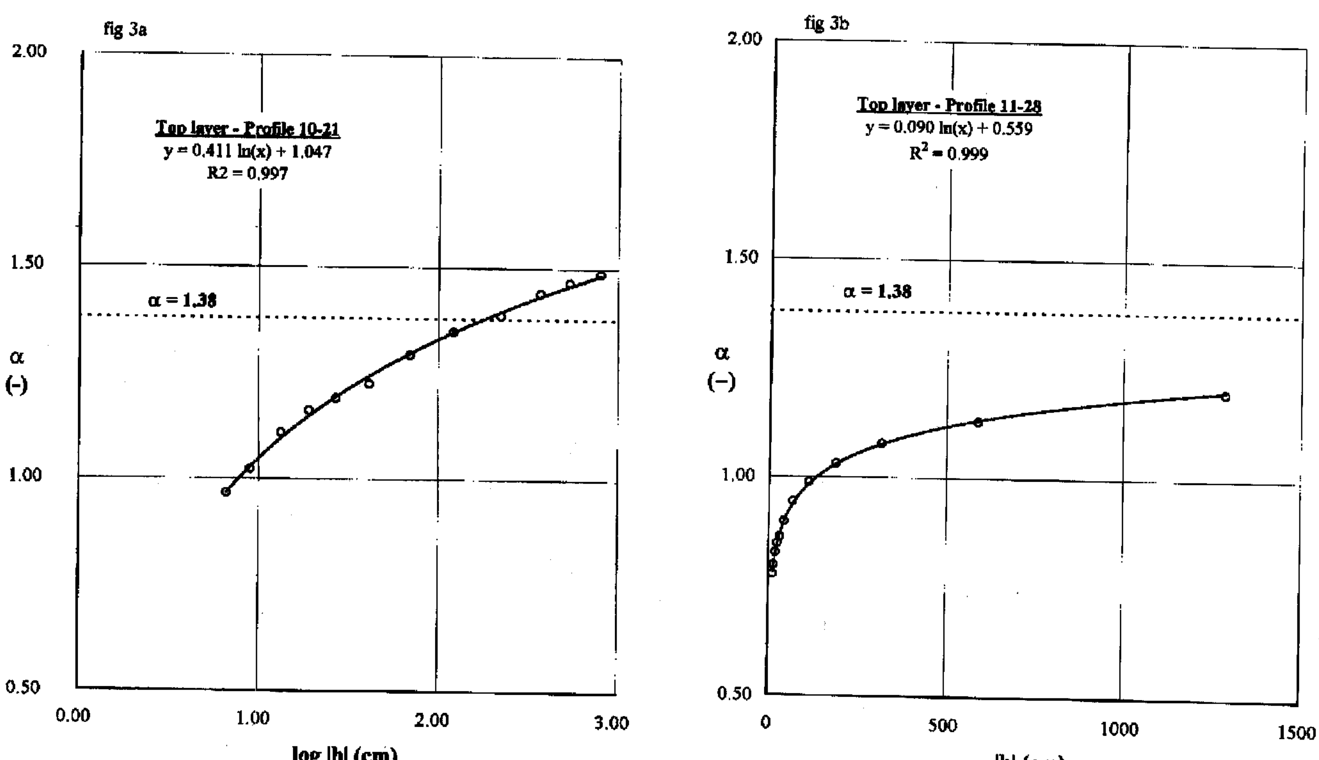

Fig. 3a,b. *Relationship between the empirical parameter α in Eqn. 1 and water potential h for: a) top layer of profile 21 unit 10 and b) top layer of profile 28 unit 11.*

pore-size distribution theory of Mualem to derive a closed-form analytical expression for the relative unsaturated hydraulic conductivity k/k_s (van Genuchten, 1980):

$$k / k_s = Se^l [1-(1-Se^{1/m})^m]^2 \quad (3)$$

where $Se = [(\theta - \theta_r)/(\theta_s - \theta_r)]$, $m = 1 - 1/n$ and the exponent l represents a tortuosity factor. With the exception of l and the value at saturation, k_s, the other parameters, namely θ_r, θ_s and m, can be estimated from SWRC data. The unknown parameter l was fixed at 0.5. There are several reasons for doing this. The applied evaporation method (Wendroth *et al.*, 1993) also provides information on the $k(h)$ relationship; hence, a preliminary analysis showed that the hydraulic conductivity relationships of quasi-totality of the soils investigated were well fitted using $l = 0.5$, with the other parameters being close to those used in the above-mentioned procedure. Moreover, Nielsen and Luckner (1992), studying some theoretical aspects to estimate initial parameters and range limits in the identification of parameters describing SWRC and hydraulic conductivity, recommend using $l = 0.5$ as initial value of estimation procedure and suggest a range limit of ± 50%. The main uncertainty was related to the estimation of saturated hydraulic conductivity. To apply the cited model, it is necessary to estimate k_s with the available data set. Compared to SWRC models, fewer indirect methods have been developed for k_s and in most cases accuracy is limited by the large variability of the parameter. As with the SWRC, there exist purely empirical methods based on regression analysis with observed data (Jabro, 1992; Rawls *et al.*, 1992) and semi-empirical models such as those proposed by Brutsaert (1968) and by Mishra and Parker (1990). The conceptual framework of these two methods is very similar; for the present study, the method of Mishra and Parker was preferred because it is based on the same schematisation of Eqn. 3. The following simplified relationship is used to determine the value of k_s:

$$k_s = c(\alpha_{\mathrm{VG}})^2 \sqrt{\theta_s - \theta_r}^{\,5} \quad (4)$$

with θ_s, θ_r and α_{VG} representing the van Genuchten parameters for SWRC and c being an empirical parameter. From the comparison between the results of Eqn. 4 and the laboratory k_s values measured on the undisturbed soil samples set, a constant value of 0.9 was assigned to the parameter c.

APPLICATION OF THE CALIBRATED MODEL FOR ESTIMATING SOIL HYDRAULIC CHARACTERISTICS FOR EACH SOIL MAP UNIT

The calibration functions were used to determine the SWRC for each location where textural information was available. As the water potential h_i in the generic i^{th} texture range can be expressed as a function of corresponding pore radius r_i through the capillary equation, Eqn. 1 can be re-written as follows:

$$r_i = R_i \sqrt{4en_i^{[1-\alpha(r_i)]} / 6} \quad (5)$$

The pore radius r_i represents the unknown in Eqn. 5 and can be determined by means of iterative algorithms for each pair of values $[W_i, R_i]$ given in the PSD curve. The plots of Fig. 4a and 4b demonstrate that knowledge of the characteristic function $\alpha(h)$ improves the estimate of SWRC from PSD significantly, compared to the original Arya and Paris method with $\alpha = 1.38$.

In the case of PSD curves given in Fig. 2, the calibration procedure was applied by using the $\alpha[h(r)]$ relationships of Fig. 3a; the resulting SWRCs are shown in Fig. 5a. Obviously, the variability of the SWRC reflects the variability of particle size-distribution within the units. Such data can be used subsequently for fitting the van Genuchten closed form of the SWRC and hydraulic conductivity function as described above. The $k(h)$ curves of units 10 are shown in Fig. 5b.

DISCUSSION OF POTENTIAL ERRORS IN THE CALIBRATED MODEL

The calibration procedure was tested by comparing four SWRCs obtained by undisturbed sampling and by means of the procedure illustrated above. The results are displayed in Fig. 6 and refer to locations R, S, N and T; the plot shows six measured θ_m, ranging between −1 to −300 cm of potential h, and six predicted θ_p soil water content values. For lower values of potential (−300, −200, −100, and −50 cm), the predicted values are underestimated at locations R, S and T but not at location N; for higher values of soil water potential (−1 and −10 cm) the results were contradictory. To explain the differences between measured and predicted values, the following considerations were made: i) the calibration procedure is unable to explain completely the variability of 'structural' properties within a soil unit but only that part of the variability depending on soil texture. It is evident that the proposed procedure is 'simplified' and does not take into account all the factors that contribute to the formation of the soil structure such as organic matter, carbonates, type of clay, etc.; ii) local soil variability, which cannot be detected in such detail by the proposed procedure, induces errors in the estimation, as in the case of location N. In fact, after the calculation, a checking survey was performed at location N and a very small area of different material was found. This location was left to show that such an error is intrinsic in any estimation procedure.

DERIVATION OF FUNCTIONAL PROPERTIES FROM SOIL WATER BALANCE SIMULATIONS

The numerical model SWATRE (Belmans *et al.*, 1983) was used for simulating one-dimensional unsaturated

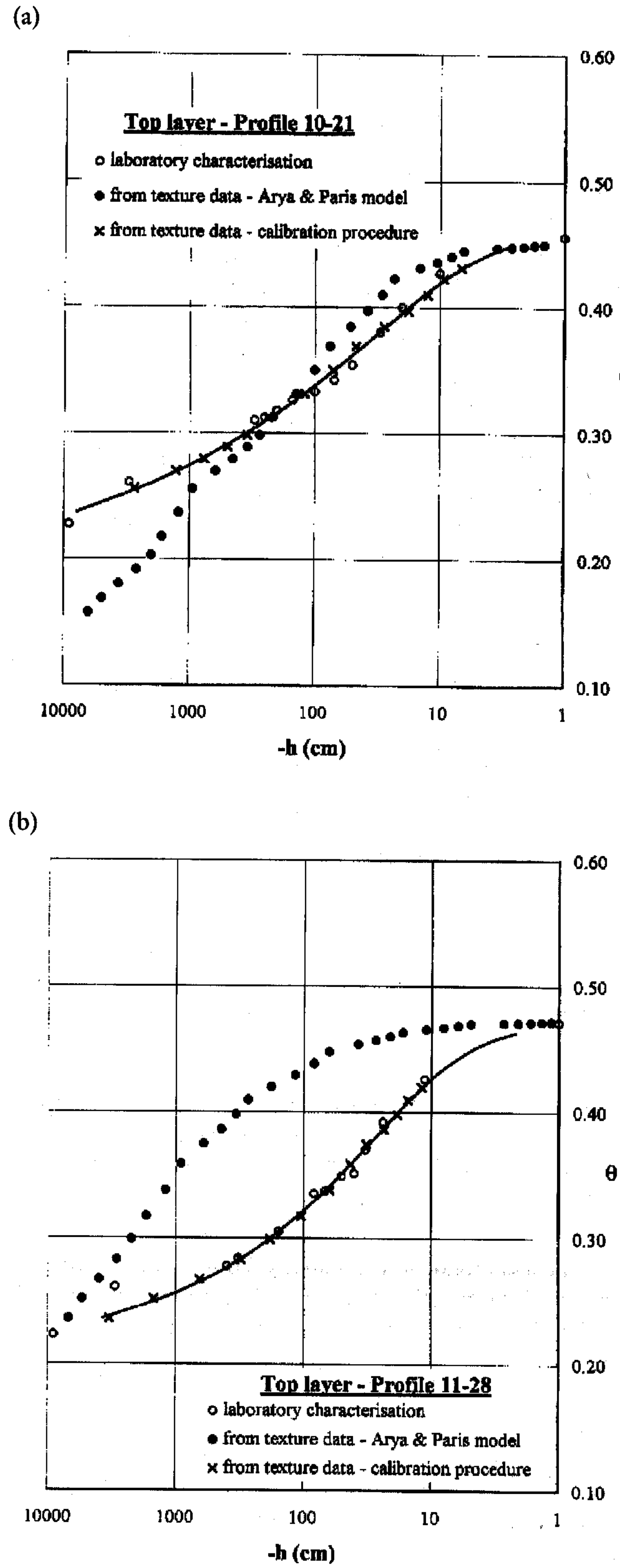

Fig. 4a,b. *Comparison of water retention curves determined in laboratory, with calibration procedure and with the original Arya and Paris method for: a) top layer of profile 21 unit 10 and b) top layer of profile 28 unit 11.*

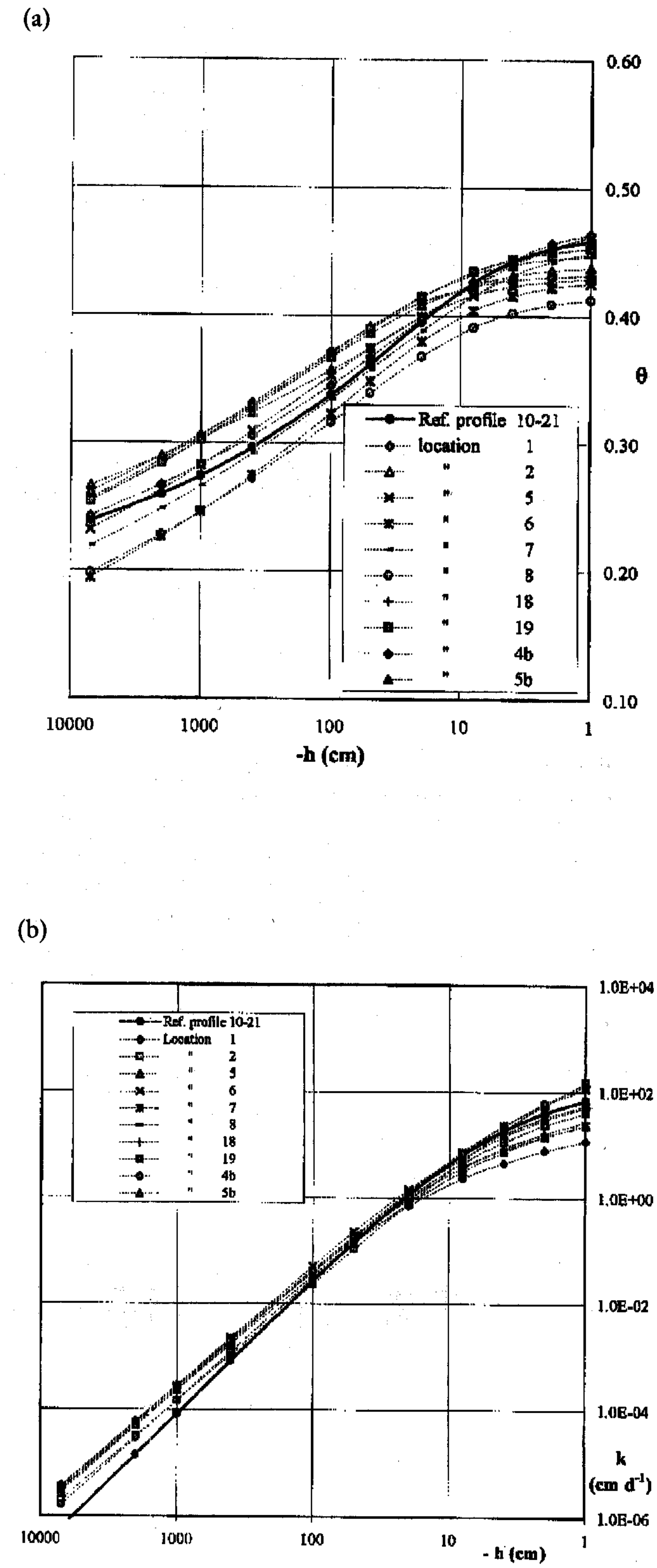

Fig. 5a,b. *a) soil water retention curves and b) hydraulic conductivity curves for the top soil layer of mapping unit 10 with reference profile 21.*

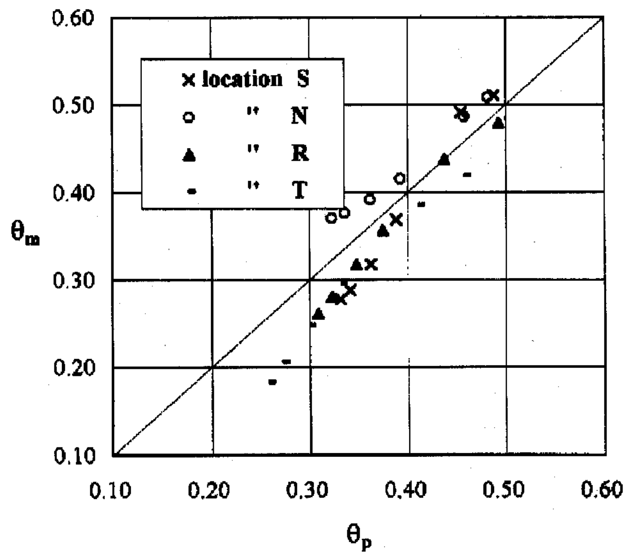

Fig. 6. *Measured θ_m versus predicted θ_p soil water content at six levels of soil water potential (ranging between –1 to –300 cm) referring to locations N, R, S, and T.*

water flow in each location where SWRC had been estimated in the previous step (Fig. 1). The model was applied for the definition of functional properties, with the aim of producing a lumped description of the hydrological behaviour of the soil profile under given assumptions.

In this study, functional properties of practical significance in irrigation management, for example soil workability, were considered. The definition of two functional properties, representing summer and winter conditions respectively, was based on calculation of the time required to reach a previously defined value of water potential at a certain depth.

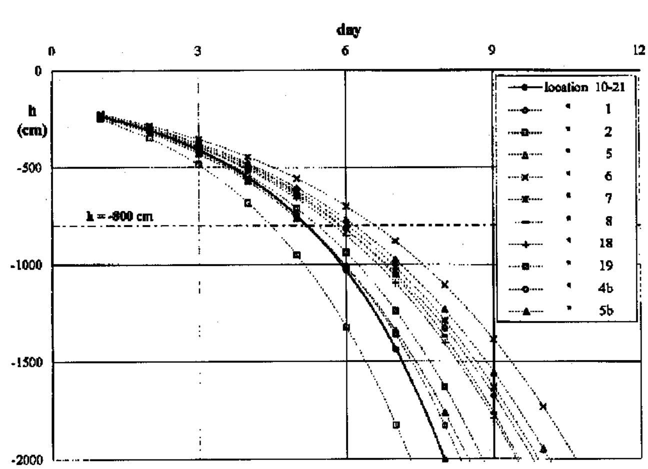

Fig. 7. *Temporal variation of average water potential between –10 cm and –30 cm for mapping unit 10, as determined by means of SWATRE model and the hydraulic functions given in Fig. 5a,b; upper boundary flux has a constant value of 0.5 cm d^{-1} (summer conditions).*

In the case of 'summer' conditions, a drying process starting from near saturation was simulated, assuming a constant potential evapotranspiration flux at the upper boundary of 0.5 cm d^{-1}, a fixed water table depth of 2.00 m for the lower boundary condition and a uniform grass cover. From the output of simulation runs, the mean value of water potential from –10 cm to –30 cm was computed for each day. In Fig. 7 the result of these calculations is shown with reference to the hydraulic functions given in Fig. 5a and 5b. The number of days needed to reach a value less than –800 cm, indicated as d_{800}, was considered as the functional property for 'summer' conditions in each location.

Similarly, the 'winter' functional property, workability, was defined as the time, d_{120}, needed to have an average water potential lower than –120 cm in the top 15 cm of bare soil; in this case, the water table depth was fixed at –1.20 m and the upper flux of evaporation was assumed equal to 0.15 cm d^{-1}. The calculation results are illustrated in Fig. 8 and can be compared to those in Fig 7.

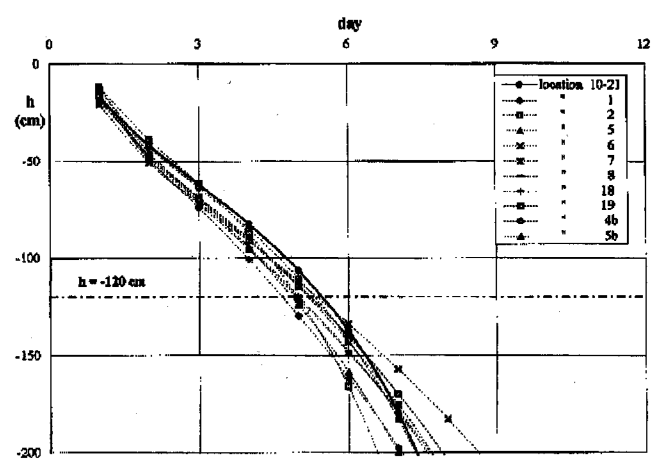

Fig. 8. *Temporal variation of average water potential within the top 15 cm for mapping unit 10, as determined by means of SWATRE model and the hydraulic functions given in Fig. 5a,b; upper boundary flux has a constant value of 0.15 cm/d (winter conditions).*

The less pronounced variability, both within and between units, of the functional property d_{120}, corresponding to the 'winter' conditions, as compared to d_{800} can be explained by the fact that, during the wet season, upper and lower boundary conditions (limited evaporation fluxes, shallow water table) have a greater effect on the response of the hydrological system than the variability of soil hydraulic properties. Indeed, this result was confirmed by field experience and long-term phreatic surface monitoring.

DELIMITATION OF SOIL HYDRAULIC HOMOGENEOUS AREAS FROM SPATIAL DISTRIBUTION OF FUNCTIONAL PROPERTIES

The resulting spatial distribution of the functional properties thus derived was used to identify areas with similar hydraulic behaviour. The soil map (Fig. 1) was reclassified according to the spatial distribution of the functional property d_{800}. Due to the more pronounced variability of soil hydraulic properties when considering the 'summer' conditions as described by the functional property d_{800}, it was possible to identify sub-areas, within each soil unit, with typical values of d_{800}. The exception to this is unit 11 (reference profile 30), where the variability of d_{800} suggests the need for further investigations.

Fig. 9 shows the new soil hydrological units superimposed on the old soil map units. In this example, the boundaries of the new map units were drawn both according to a discrete technique of interpolation using external landscape features (Burrough, 1986) and roughly visual delimitation based on the information obtained in this study. Continuous interpolation techniques such as kriging will be possible, when a larger set of observation points is available and a robust two-dimensional semivariogram can be estimated.

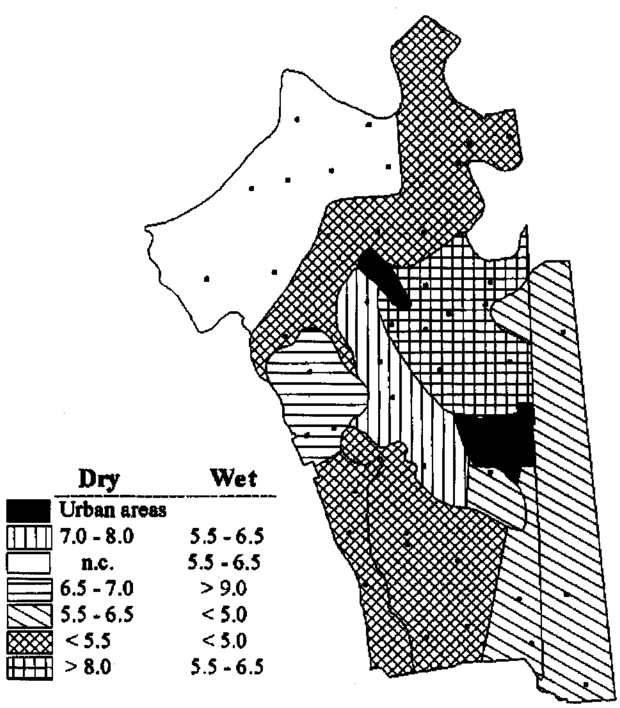

Fig. 9. *Hydrological map unit boundaries superimposed on the soil map of Fig. 1. The distinct patterns correspond to different values of the functional properties d_{800} (Dry); n.c. stands for not classified; the values of the functional properties d_{120} (Wet) are shown in the legend.*

As a practical output, one set of soil hydraulic parameters describing $\theta(h)$ and $k(\theta)$ might be defined for the main soil horizons in each of the sub-areas shown in Fig. 9.

Due to the above-explained minor variability, a map of the functional property d_{120} does not provide any additional information, as shown by the d_{120} values in the legend of Fig. 9.

Concluding Remarks

The output produced was used to refine pedological soil map boundaries with the objective of using them to apply distributed hydrological models. Furthermore, such information could in turn be used to improve the strategy for allocating water in irrigated areas.

As remarked by van Genuchten and Leij (1992), direct measurement methods are required for site-specific problems. Moreover, while indirect methods, based on more easily measured soil properties, are useful for problems involving scales of 1:50 000 or smaller, their accuracy for site-specific applications on detailed scales of 1:10 000 or larger still needs improvement. In such cases, the procedure described here addresses some of the main issues involved. The experience of this case-study suggests that the correct application of the indirect methods proposed for predicting soil hydraulic properties at detailed scales imposes the basic requirements of a pedological study in order to associate a part of the variability of the hydraulic properties to pedogenetic factors (discrete variability). Moreover, in each pedological unit, the hydraulic property variability is explained by means of the textural variability (continuous variability). The need to define pedological units clearly is due to the fact that the relationship $\alpha(h)$ is supposed to be specific in each horizon, and a function of the texture-structure combination. Hence, soils with similar texture can have completely different $\alpha(h)$ relationships. In other words, $\alpha(h)$ represents a sort of translation of soil texture into soil structure for each defined soil horizon. As stated above, the procedure cannot explain completely the variability of the 'structural' properties within the units but only that part linked to the soil texture. However, by means of correlation techniques it is possible to take into account the variability of others parameters as well as texture. To summarise, i) the pedological study has to be accurate in the identification of the representative profile, ii) the soil hydraulic parameters have to be suitably calibrated and iii) a procedure has to be defined to characterise the hydrological behaviour of the whole soil profile.

Acknowledgements

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